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The application of Pareto frontier methods in the multidisciplinary wing design of a generic modern military delta aircraft[1]

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Abstract

As a partner in the EC Framework IV "FRONTIER" project, DERA has investigated the application of a genetic algorithm (GA) and Pareto frontier methods to optimise the trade-off between multiple design objectives. A Pareto frontier is defined as the limit of design space beyond which one attribute of a design cannot be improved without detriment to another. DERA has applied the software produced within the project to the multidisciplinary design of the wing of a generic modern military delta aircraft, to trade-off the conflicting design requirements of range and agility. This paper recounts DERA's experience of the methods as an approach to the solution of a trial multidisciplinary design and optimisation (MDO) problem together with some of the results produced. Details of the software produced within the project are provided, along with conclusions and recommendations from its use.

Introduction

A characteristic of both military and civil aerospace engineering is the diverse range of disciplines contributing detailed information to the design task, such as aerodynamics, structures, signatures, manufacturing and support costs. The activities of these disciplines are commonly separate, and rely upon highly developed software tools for local analysis or optimisation of the discipline-based problem. In order to produce a viable design, the various disciplines must exchange subsets of their data, which will act as configuration definition or constraints data for the other disciplines. A MDO approach will simplify this process, whilst reducing design time and aiding the development of an equivalent or superior product. A detailed examination of the requirements and future potential for MDO, from a UK perspective is covered in reference 1.

The European Commission Framework IV project, "FRONTIER" [2] examined the increasingly important role of MDO in the design and assessment of new equipment. It explored the application of modern computing methods to link existing, complex engineering software tools in an easily accessible user environment, to enable engineers to optimise the trade-off of multiple objectives during the product design phase.

The project was a collaborative venture involving eight partners from industrial, academic and research establishments, and covered a wide range of engineering sectors, from household goods to aircraft. The partners were categorised according to their role within the project as either MDO users: DERA, British Aerospace (BAe), Daimler-Chrysler Aerospace (DASA), Calortecnica and Zanussi; or system suppliers: the University of Bergen, the University of Trieste and the University of Newcastle-upon-Tyne.

DERA investigated, in conjunction with BAe, the application of the multidisciplinary design tools produced by the 'supplier' partners to the wing design of a generic modern military delta aircraft. The user trial for the study comprised a tractable problem typical of aerospace concept development and design activities, which focused on examination of the effect of detailed aerodynamic and structural wing design on the overall aircraft performance. As such it was representative of the work of both BAe and DERA in their respective roles as equipment suppliers and advisors to the end users.

DERA user trial

The main aim of the DERA user trial was to guide the development and test the software produced by the supplier partners within the context of a typical aerospace design problem. The design problem selected for the software test phase involved the inter-disciplinary optimisation of the wing of a generic modern military aircraft (as pictured in figure 1a). To keep the problem at a suitable level of detail, only two disciplines were involved; aerodynamics and structures. It was intended that the user trial would prove the principle of inter-disciplinary optimisation, by using two already closely linked disciplines. The principle could then be extended in the future to include further disciplines, such as signatures and cost modelling.

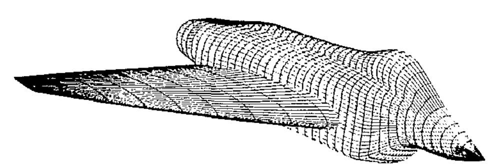

Figure 1a; CFD wing/body half model

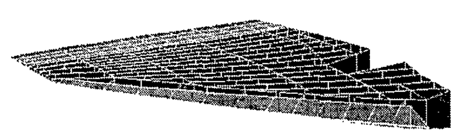

Figure 1b; Finite element wing model (upper skin omitted)

The discipline specific models for the user trial were provided by BAe, and are shown in figures 1a and 1b. The objective of the study was to improve both the transonic penetration range and supersonic agility, as measured in terms of sustained turn rate (STR), of the aircraft. These conflicting performance requirements have historically been difficult to combine in a single design; a 'bomber' aircraft tends to have long range capability and poor manoeuvrability, whilst a 'fighter' aircraft generally exhibits good agility but short range.

Aerodynamic design optimisation is carried out at DERA using the Constrained Optimisation Design of Aerodynamic Shapes (CODAS) [3] software tool. This generally uses the Structured and Unstructured Numerical Analysis (SAUNA) computational fluid dynamics (CFD) suite [4] for the

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aerodynamic analysis. CODAS uses a gradient-based optimisation algorithm, which attempts to minimise a user-defined objective function, subject to user-defined constraints, by varying the cross-sectional shape of the wing. The objective and constraint functions can be built from aerodynamic performance parameters (such as coefficient of lift, C_L and coefficient of drag, C_D), in addition to geometric parameters, such as thickness-to-chord ratio (t/c) and curvature.

DERA's structural design optimisation is conducted with the Structural Analysis and Redesign System (STARS) [5] which employs NASTRAN for the finite element analysis. The method uses a gradient-based optimiser to vary the thickness of the structural members, subject to constraints such as strength and stiffness, in order to minimise the overall structural mass.

Sequential operation of these two detailed discipline-based tools by their respective specialists is the traditional approach to an aerodynamic/structural wing design.

To reduce the complexity of the MDO task, the wing planform shape and location were fixed with respect to the fuselage. Initial studies into the performance of the aircraft at the required design points of transonic range and supersonic agility, indicated that the main aerodynamic drivers behind the differences in capability were wing thickness and wing camber due to their effect on lift, drag and internal fuel volume. The wing was therefore parameterised using the following 4 design variables:

i. t/c at the wing root
ii. t/c at the wing mid-semi-span
iii. t/c at the wing tip
iv. wing camber (3 discrete levels)

From the structures perspective, the objective was to minimise the mass of the wing structure, as this benefits both range and STR performance measures.

The output of the aerodynamic analysis of a single design instance included results such as transonic and supersonic C_L and C_D and internal fuel volume, whilst the structural analysis output the wing structural mass. These results are all low-level performance parameters specific to each discipline. In order to carry out a high-level optimisation of the wing as an element of the whole aircraft, incorporating both disciplines, high-level performance measures (such as range and STR) were required. Detailed models exist within DERA to analyse the performance of an aircraft as a whole based upon these performance parameters, but their use would have led to an over-complication of the user trial and have incorporated another detailed discipline into the high-level optimisation. Therefore for this user trial, simple equations derived from basic mechanics were used to convert the performance parameters detailed above into the high-level performance measures of range and STR.

Transonic penetration range was estimated for this approach using the Breguet range equation thus:

$$R = \left(\frac{Ma}{c'g}\right)\frac{L}{D}\ln\left[\frac{1}{1-(W_{fuel}/W_{take-off})}\right]$$

where:
R = range (m)
M = Mach number
a = speed of sound ($m.s^{-1}$)
c' = specific fuel consumption ($kg.N^{-1}.s^{-1}$)
g = gravitational constant ($m.s^{-2}$)
L = lift (N)
D = drag (N)
W_{fuel} = weight of fuel at take-off (N)
$W_{take-off}$ = total weight of aircraft at take-off (N),

and supersonic STR was estimated thus:

$$\omega = \frac{g}{Ma}\sqrt{\left(\frac{\frac{1}{2}\rho(Ma)^2 SC_L}{mg}\right)^2 - 1}$$

where the terms are as before, and:
ω = turn rate ($radians.s^{-1}$)
ρ = air density ($kg.m^{-3}$)
S = gross wing area (m^2)
C_L = coefficient of lift
m = mass of the aircraft (kg).

The FRONTIER framework

The software framework for MDO developed within the FRONTIER project comprises three separate functional entities; a graphical user interface (GUI), high-level optimisers, and a decision support tool as described below.

Graphical user interface (GUI) : The GUI was written by the University of Bergen, Norway [6, 7] and is intended to provide a user-friendly and easily accessible front-end to the rest of the FRONTIER system. The GUI provides a generic front-end for MDO which is applicable to most industrial design problems and consists of two main elements. The first element handles the interface with the user, and the second element is a framework to manage execution of the various analysis and optimisation processes involved in the task. The GUI interface is designed to be used across a network of heterogeneous platforms, and has been based on the JAVA language, in conjunction with HTML internet web page type screens. The portability of the GUI interface element between various hardware and software environments is therefore greatly enhanced, whilst also remaining highly configurable.

The GUI framework element involves the sequencing of the various stages of the MDO task based upon a user-defined logic script that indicates the required data files and software modules to be run. This relies upon an integral part of the GUI tool to automate the compilation of the run-time scripts needed to execute the discipline based legacy codes required for the analysis. The GUI framework deals with all the interactions between the various software modules as required, with only simple operations required of the user in order to set-up the optimisation problem. As part of the framework element, the Common Object Request Broker Architecture (CORBA) industry standard for message passing is used for communication between the various modules. This allows the modules to exist on separate, heterogeneous hardware platforms. The use of JAVA and CORBA will ensure the longevity of the software and enable future developments to the MDO framework to be readily incorporated.

Optimisers : The FRONTIER software includes two optimisers; a multi-objective genetic algorithm (MOGA) and a simple gradient-based method, both of which were programmed by the University of Trieste, Italy [8, 9]. The MOGA is the main optimiser for FRONTIER, and consists of a generational GA which can be appropriately configured by the users to suit their individual optimisation problem. Examples of the settings that can be altered by the user include the number of individuals and generations required, the probabilities of crossover and mutation and the generational strategies (steady-state or standard) that are to be employed in the optimisation. Based upon either a random or user-defined initial set of individuals, the MOGA searches the design space for non-dominated solutions to the problem, subject to any user-defined constraints, which are represented as fuzzy penalty functions. Having thus explored the design space fully, the designs that form the non-dominated limit of the design space (ie. the Pareto frontier) can be filtered from the whole population, using the tools provided in the GUI.

To complement the MOGA, a gradient-based optimisation routine, based on the Broyden-Fletcher-Goldfarb-Shanno (BFGS) method is also supplied. This can be used to maximise a single objective function starting from a user-defined individual. With a choice of finite differencing schemes and the ability to use weighted combinations of the multiple objectives, the BFGS optimiser can be used to refine the current optimum as identified by the MOGA in a chosen region of design space.

Decision support tool : The multi-criteria decision maker (MCDM) has been written by the University of Newcastle-upon-Tyne, U.K. [10, 11] and is intended as an aid to the design engineer. The method employs the principles of utility functions to assess the relative merit of a series of designs, in order to assist the designer in selecting the alternative which most closely matches the user requirements. The facilities provided by the MCDM become particularly relevant at the later stages of the optimisation design process when a defined Pareto frontier set of designs can be compared against each other, and then ranked according to a declared set of user preferences. The subsequent output can then be used within the gradient-based optimiser to further refine the Pareto frontier in the area of interest to the designer.

The procedure used to rank the designs is based upon declared user preferences or indifferences for one design compared to another in the set of candidate designs. In addition, weightings can be applied between design variables to accommodate any specific needs. These judgements are used to calculate utility functions for each of the design variables. The software uses an exhaustive search method to refine the magnitude and curvature of each utility function, with the resolution of the search being refined as the best solution is identified. If no solution is possible, it is assumed that there is an inconsistency in the initial declared preferences, and the method suggests to the user which preferences should be reviewed. Once a solution is found, the composite utility function, formed from the amalgamation of the utility functions for each design variable, is used to rank the candidate designs. The magnitude and curvature of each of the design variable utility functions is also output, for use within the BFGS optimiser if required.

The general method for operation of the framework is firstly to link the existing analytical tools to the framework, using tools provided within the GUI. This provides the analytical functionality for the design optimisation process. The framework then needs to be configured for the specific design problem, such as number of design variables, number of constraints and the order in which the analytical tools will be used. Once these tasks have been carried out for a specific design problem, they do not need to be repeated. The optimisation is then usually begun with the MOGA for a specific number of individuals and generations, so that the design engineer can ascertain the nature of the design space, and if necessary adjust or incorporate further constraints. Following a successful MOGA optimisation and identification of the resulting Pareto frontier, the MCDM tool can then be used to rank a sub-set of the designs, in order to concentrate any subsequent optimisation effort into the area of design space of most interest to the design engineer. The best MOGA

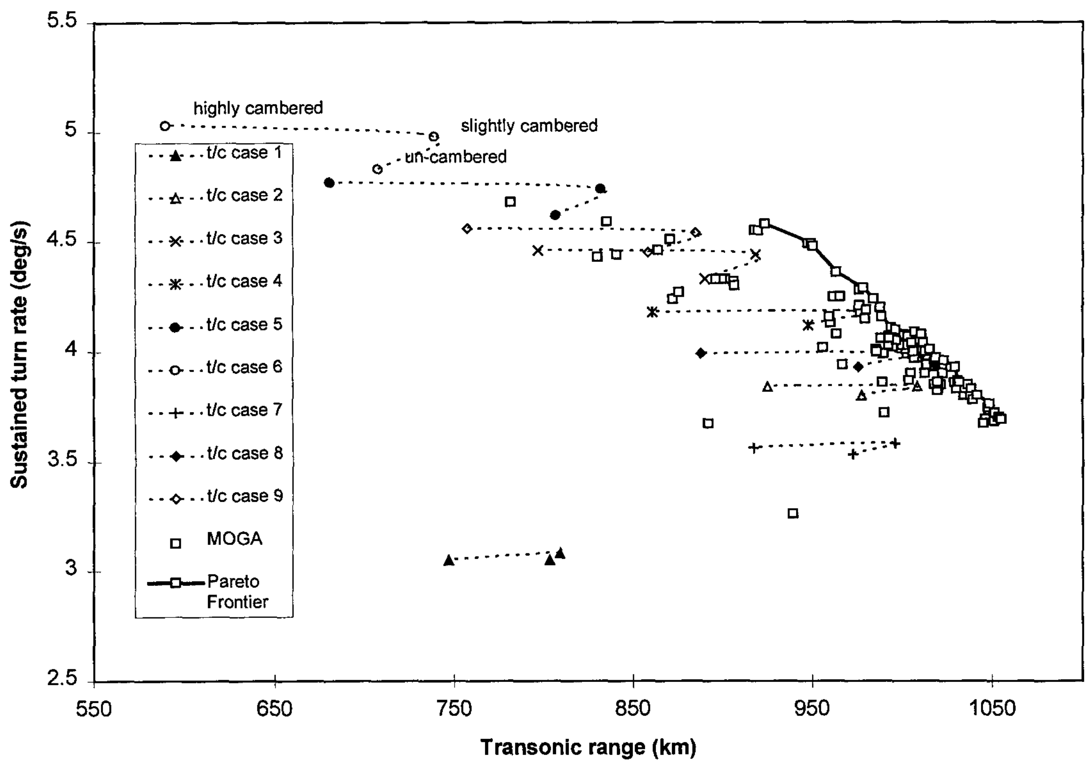

Figure 2; Initial response surface and Pareto frontier

generated design, calculated from the user requirements, can then be used as a starting point for the gradient-based optimisation to search for an improved design.

When using the FRONTIER software framework, the user has little direct interaction with the optimisers or decision support tool as all of the configuration and initiation of these modules is carried out using the GUI. It is therefore possible for a user inexperienced with the hardware and software of the host machine(s) to carry out an optimisation task.

Results

It was originally intended to encompass both CODAS and STARS within the DERA FRONTIER user trial, however cost implications associated with the coupling of a GA to such highly computationally intensive, low-level optimisation tools precluded this. Instead, an approach was adopted in which an initial set of designs were analysed with the detailed discipline tools, and the results used to populate a response surface. This could then be coupled directly to the FRONTIER system to identify the multidisciplinary optimum, with relatively little further computational cost beyond that required for the initial population of the response surface.

Accordingly, for the aircraft wing user trial an initial population of 27 designs were analysed with the detailed design tools to create a response surface which was a near quadratic for each of the design variables. These were produced from a set of 9 spanwise thickness profiles, each of which had 3 levels of camber applied to it; 'none', 'slight' and 'high'. The 'high' camber case was taken from initial studies carried out using CODAS, and the 'slight' camber was half of the 'high' camber case. For each design, estimates of its range and agility were made using the equations described earlier. It has been assumed that the wing structural mass is independent of the wing camber. The high-level performance measures for the initial response surface population are shown in figure 2.

For the majority of cases, the highly cambered wing has the best supersonic STR, but the worst transonic range. This is because such wings are efficient at the high-lift design point, but must be flown at a reduced angle of attack to achieve 1g flight. This tends to produce shock waves on the underside of the wing, just aft of the leading-edge, which increases the drag, and hence reduces the aircraft's range. However, the un-cambered wings generally have the least turn rate, due to their reduced efficiency at high lift, but need to be flown at an increased angle of attack in order to generate the required lift for 1g flight. This tends to produce shock waves on the upper surface of the wing, again aft of the leading-edge, though these tend to be weaker than those on the highly cambered wing, and hence the aircraft show an improvement in range. For each spanwise thickness case, the slightly cambered wing has the best range. This is because it produces relatively weak or no shock waves for the range design point, yet is relatively efficient at the supersonic high lift design point, hence giving a good turn rate.

Interestingly, the results for each of the spanwise thickness cases shown in figure 2 are themselves low-level Pareto frontiers. These are approximated by the dotted lines, however it is not possible to determine the full extent of each curve from the available data.

The response surface was then coupled to the MOGA and an optimisation run of 10 generations, each of 32 individuals was performed. The results are shown in figure 2, together with the initial 27 designs for comparison. It can be seen that the MOGA has produced a wide ranging set of design instances, most of which show an improvement over the initial 27 designs. It is postulated that the Pareto frontier would not be

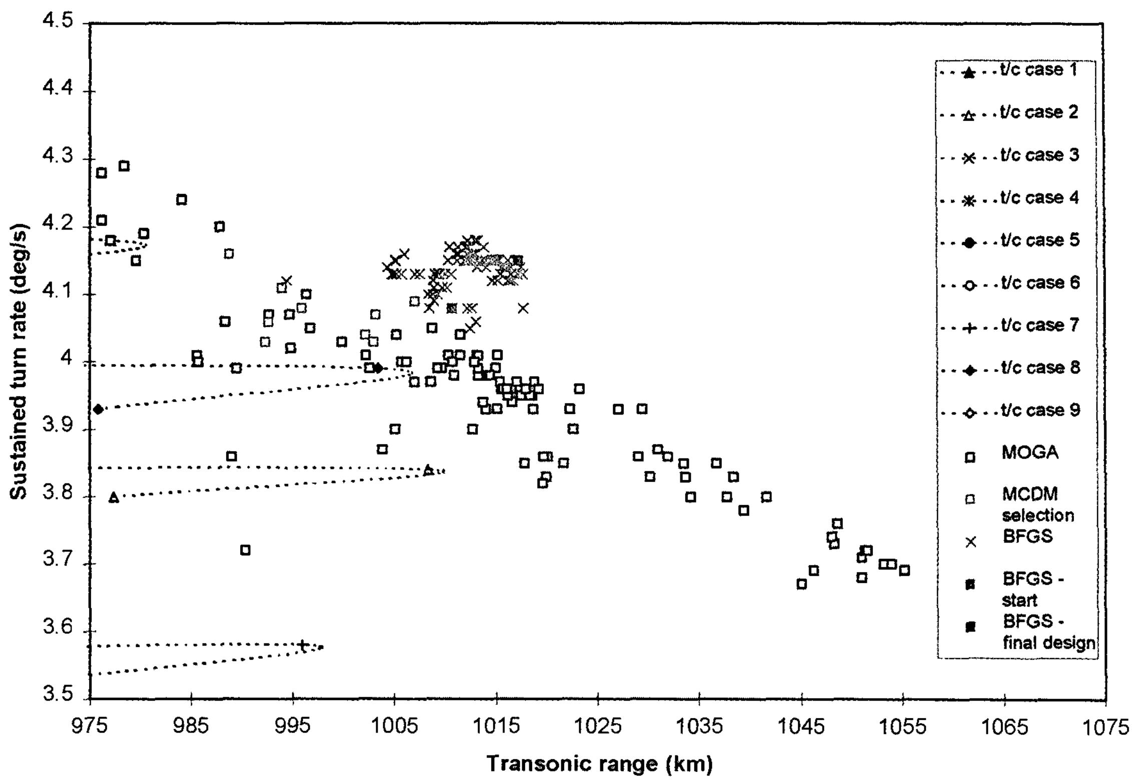

Figure 3; Refined high-level optimum design advanced a great deal from the position shown in figure 2, without recourse to a very large number of generations and individuals within the MOGA. However, the Pareto frontier shown provides a useful aid to the design engineer, in that it demonstrates the nature of the design space involved.

To illustrate the use of the framework to optimise the wing to satisfy a defined set of user performance requirements, the designs identified by the MOGA on the Pareto frontier were then refined with the aid of the MCDM and gradient-based optimiser. Based on an assumed user requirement to maximise aircraft range and attain at least a 4°/s STR, a series of designs on and close to the Pareto frontier in the region of the required STR were passed to the MCDM decision support tool.

Several pairwise preferences were provided to the MCDM, together with the selection of designs from the MOGA Pareto frontier. The output of the MCDM software ranked the supplied designs, based on the indicated preferences and provided appropriate relative weightings for the objectives. The top ranked design, together with these weightings were then transferred to the BFGS gradient-based optimiser within the FRONTIER system, and a further optimisation carried out.

The results of the follow-on gradient based optimisation are shown in figure 3. It can be clearly seen that an improved design has been found in comparison to the MOGA Pareto frontier. This design is an improvement over the other designs, based on the preferences supplied to the decision support tool. It should be noted that this improved result is based upon the example user requirements of good range, and a minimum STR of 4°/s. If different user requirements had been specified, or different preferences used within the decision support tool, then it is likely that the final optimum design shown in figure 3 would be different. It is postulated that such refinement of the GA Pareto frontier could be carried out along the whole frontier, however this would require a large number of separate gradient optimiser runs, and this would have computational cost implications. Hence, the use of the decision support tool to concentrate optimisation effort only in the area of design space of interest to the designer.

Conclusions

The use of a GA allows the nature of the design space to be assessed, in addition to the well-publicised benefits for finding the global optimum of a problem. However, the shortcomings of such an approach are generally cited as being the relatively slow 'convergence' of such algorithms, in that they require a large number of design instances to be analysed to achieve the optimum design. It has been shown by these results that these difficulties can be partly addressed by the use of a GA in conjunction with a gradient-based optimiser. The GA can be used to populate the design space to sufficient detail for the design engineer to choose an area of interest, and then the designs can be refined just in that area, by the more efficient gradient-based method.

The critical step of the approach described above, is the transition from the more globally orientated GA, which may be using multiple objectives, to the more focused, single objective gradient-based approach. A great deal of time and effort can be spent in trying to devise weightings for the multiple objectives, in order to combine them into a single objective function. The use of a decision support tool at this stage, such as that in the FRONTIER system, can be very beneficial. Not only does it calculate which is the current best design, and therefore a suitable starting point for any subsequent gradient-based optimisations, but it also calculates the relative weightings of the multiple objectives. These calculations are based on the initial information provided by the designer, and therefore reflect the user requirements in simple quantitative terms. However, for such decision support tools to be of use to the design engineer, the sensitivity of the output to the input should be examined closely, and the output only taken as guidance, rather than the definitive answer. Then, such tools can be highly valuable to the decision making process.

The use of a response surface approach, although utilised by this project primarily because of cost considerations has proved to be a success. It required the highly specialised low-level analysis tools to be used only by the respective specialists, and therefore the integrity of the data input to the response surface was assured. This avoids the possibility of the optimiser requesting analysis of designs which are incompatible with the underlying philosophy of the specialist analysis tool. In addition, when used with a GA a response surface requires relatively little computational effort to interrogate, in comparison to direct coupling of the analysis tools to the optimiser, and so a far wider reaching study can be performed. Similar findings are stated in reference 12.

The FRONTIER software tools at their current version of release, whilst clearly providing a valuable facility for MDO, have been developed over a relatively short period of time, and must be regarded as a pilot implementation of the techniques. As such, DERA has identified limitations in the current abilities of the framework. For instance, the FRONTIER system currently allows only for the use of the in-built optimisers, which are closely integrated with the rest of the framework. It is hoped that when the system matures the optimisers will be placed on the same level as the other software modules which perform tasks such as detailed design, design simulation, or performance assessment. This would allow the user to implement an in-house or "off-the-shelf" optimiser to suit the design task in hand, whilst also facilitating more advanced branching between tasks and disciplines as the design run progresses. In addition, the implementation of a common product model based upon industry standards such as the Standard for the Exchange of Product Data (STEP) would provide a database which could be used to store and access current and past optimised designs, without the need to re-run design tasks. It is hoped that the future exploitation of the FRONTIER software by a commercial vendor will address such shortcomings, and produce a FRONTIER framework that can be utilised as the basis for a generic MDO framework, applicable to a large number of engineering sectors in addition to aerospace.

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DISCUSSION

Session II, Paper #13

Mr Perrier (Dassault Aviation, France) asked whether CORBA really worked for multiple users in a networking environment.

> **Mr Fenwick** replied that CORBA constructs are used to handle all the communication between the various software modules within the FRONTIER software. He believed that as an industry standard, CORBA allows easy and reliable communication between modules, whether they are hosted on one machine or many. Consequently, FRONTIER software is platform independent and allows easy use of network machines.

Mr Perrier asked how many GA iterations were used.

> **Mr Fenwick** noted that in the example presented there were 10 generations of 32 individuals in each generation, however not all are shown on the graphs as some of these were infeasible, i.e. they broke the imposed constraints.